Can Deflagration-Detonation-Transitions occur in Type Ia Supernovae?

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ABSTRACT

The mechanism for deflagration-detonation-transition (DDT) by turbulent preconditioning, suggested to explain the possible occurrence of delayed detonations in Type Ia supernova explosions, is argued to be conceptually inconsistent. It relies crucially on diffusive heat losses of the burned material on macroscopic scales. Regardless of the amplitude of turbulent velocity fluctuations, the typical gradient scale for temperature fluctuations is shown to be the laminar flame width or smaller, rather than the factor of thousand more required for a DDT. Furthermore, thermonuclear flames cannot be fully quenched in regions much larger than the laminar flame width as a consequence of their simple "chemistry". Possible alternative explosion scenarios are briefly discussed.

Subject headings: hydrodynamics, stars: supernovae: general

1. Introduction

The delayed detonation scenario for Type Ia supernova (SN Ia) explosions asserts that a Chandrasekhar mass C+O white dwarf undergoes a thermonuclear explosion in two distinct modes: an initial turbulent deflagration (flame) phase that preexpands the star, allowing the abundant production of intermediate mass isotopes observed in SN Ia spectra, followed by a detonation that accounts for the high material velocities and the strength of the explosions (Khokhlov 1991; Woosley & Weaver 1994). Both modes are assumed to be linked by a deflagration-detonation-transition (DDT) that occurs either during the first expansion phase or after a partial recollapse of the star (Arnett & Livne 1994). The background density of the DDT, $\rho_{\rm t}$, is often referred to as the leading candidate for the physical parameter corresponding to the observed correlation of peak luminosity and light curve shape (Höflich et al. 1997; Nomoto et al. 1997).

Despite the apparent success of one-dimensional delayed detonation models in reproducing many features of observed SN Ia spectra and light curves (Höflich et al. 1997), a quantitative investigation of DDTs in supernovae has begun only recently. Both dimensional analysis and numerical simulations indicate that a turbulent thermonuclear flame front driven on large scales by the Rayleigh-Taylor (RT) instability falls short of sonic propagation by at least one order of magnitude (Niemeyer & Hillebrandt 1995; Khokhlov 1995; Reinecke et al. 1998a), making early proposals for DDT by direct shock formation seem implausible. An alternative route to detonations in supernovae based on the induction time gradient mechanism (Zeldovich et al. 1970) was recently proposed (Khokhlov et al. 1997b; Niemeyer & Woosley 1997). It requires a sufficiently large region of unburned fluid to be preconditioned in a manner that establishes a uniform temperature gradient across it. For predominantly temperature dependent reaction rates, this gradient can be mapped onto a gradient of induction times and hence onto a phase velocity for the spontaneous burning wave that sweeps across the region. When certain criteria regarding the fuel mixture fraction and the size of the region are met (Sec. 2), the pressure released by the burning wave may form a self-sustaining reaction-shock complex, i.e. a detonation. Note that no microscopic transport nor high fluid velocities are needed for the runaway to detonation; instead, the problems of the earlier proposals for DDT that needed supersonic turbulent flame speeds are now entirely passed on to the preconditioning of the gradient region. Owing to the absence of walls or obstacles, the preferred locations for DDT in confined systems, preconditioning in supernova explosions can only be attributed to mixing in a turbulent flow field. However, it will be shown in Sec. (3) that successful preconditioning entails a degree of synchronicity that is irreconcilable with subsonic turbulence.

In this paper, it will be argued that turbulent mixing in large systems does not, in general, give rise to uniform gradients on large scales (Sec. (3)). Furthermore, even if locally isolated regions are considered, the robustness of thermonuclear flames with respect to turbulent quenching disfavors the emergence of sufficiently well-mixed regions for DDT. We conclude that unless we are missing an important piece of information, the physics of unconfined turbulent thermonuclear flames appears to allow transitions to a detonation only in the case of rare fluctuations instead of providing a robust framework for DDT. Some alternative explosion scenarios will be outlined in Sec. (4).

2. Prerequisites for deflagration-detonation-transitions in supernovae

Assuming that there are no natural sources of shocks in the turbulent flame brush of a supernova explosion (for a possible exception, see the description of ATC in Sec. (4)), such as corners or obstacles in terrestrial combustion experiments, the only way to create a pressure spike that turns into a detonation is by burning a certain critical volume, $V_{\rm c} \sim l_{\rm c}^3$, of fuel within a time comparable to or less than its sound-crossing time, $t_{\rm s}(l_{\rm c}) \sim l_{\rm c}/u_{\rm s}$. This can be achieved in two very different ways. On the one hand, turbulent deformation of the flame surface can, in principle, create a sufficiently large flame surface area to burn a given volume in an arbitrarily short time. This idea is the motivation behind the fractal model (Woosley 1990). However, a simple argument shows that this can only occur in rare fluctuations as long as the steady-state turbulent flame velocity, $S_{\rm T}$, is subsonic, since the statement of burning $V_{\rm c}$ within $t_{\rm s}$ is equivalent to $S_{\rm T} \sim u_{\rm s}$ if $S_{\rm T}$ is evaluated on the scale $l_{\rm c}$. Given that in the flamelet regime, the turbulent flame speed scales with the turbulent velocity fluctuations on each scale, $S_{\rm T}(l) \sim v(l)$, and that the latter is bound from above by the (subsonic) terminal rise velocity of buoyant RT bubbles, it is clear that this mechanism is an unlikely candidate for a robust DDT scenario (Niemeyer & Woosley 1997).

On the other hand, detonations might be created via the well-studied induction time gradient, or SWACER, mechanism (Zeldovich et al. 1970; Lee et al. 1978), whereby a combustion wave moving along a preconditioned temperature gradient coherently builds up a pressure wave that – for sufficiently large preconditioned volumes – eventually turns into a detonation (for a recent discussion, see Khokhlov et al. 1997a,b). The minimum size $l_{\rm c}$ of the preconditioned region that gives rise to a detonation in white dwarf matter was derived numerically by Niemeyer & Woosley (1997) and Khokhlov et al. (1997b). It sensitively depends on the composition and density of the fluid; however, for the purpose of this paper it is sufficient to note that in all cases, $l_{\rm c}$ is larger than the laminar flame width δ by more than three orders of magnitude.

So far, the problem has merely been shifted from the fine-tuning of the flame surface area within the critical region to that required to precondition the temperature field. In both cases, the only tool naturally available is subsonic buoyancy-driven turbulence. However, as pointed out by Khokhlov et al. (1997a,b) and Niemeyer & Woosley (1997), it is possible in principle that for a given laminar flame speed and width there exists a critical turbulence intensity such that turbulent mixing can locally extinguish, or quench, the nuclear reactions within the flame. If this were the case, turbulence might be able to mix burned and unburned material and establish an appropriately smooth temperature field. The details of this mixing process, however, were not investigated in previous studies.

Niemeyer & Woosley (1997) and Khokhlov et al. (1997a,b) used the Gibson length $l_{\rm g}$, defined as the scale where the turbulent eddy velocity is equal to the laminar flame speed, $v(l_{\rm g}) \sim S_{\rm L}$, to postulate the necessary conditions for flame quenching: if $l_{\rm g} \leq \delta$, the burning regime changes from "flamelet" to "distributed" burning and turbulence begins to appreciably affect the diffusion-reaction structure of the flame. Only in the distributed burning regime can local flame quenching take place. The criterion above was later shown to be equivalent to a definition of the flamelet regime based on the relative strengths of turbulent and thermal diffusivities (Niemeyer & Kerstein 1997). Note that for Prandtl numbers $Pr = \nu/\kappa$, defined as the ratio of viscosity and thermal conductivity, below unity this criterion is in conflict with conventional flamelet theory (Peters 1984) which relies on a comparison of the Kolmogorov length and δ; according to this definition, thermonuclear flames with $Pr \ll 1$ would never be anywhere near the flamelet regime. Recent numerical experiments favor the modified flamelet definition as opposed to the conventional one (Niemeyer et al. 1999).

Intriguingly, the transition from flamelet to distributed burning, and hence the first chance for turbulence to create large islands of preconditioned material, approximately takes place at the right transition density for DDT, $\rho_{\rm t} \sim 10^7$ g cm^{-3}, inferred from one-dimensional explosion models (Niemeyer & Woosley 1997). It could therefore provide the switch that triggers detonations in the late phase of supernova explosions, replacing a free model parameter with a physical one. To conclude this section, the combination of the gradient mechanism for DDT and the transition from flamelet to distributed burning at a density of $\sim 10^7$ g cm^{-3} may explain the bulk of SN Ia observations, but it crucially hinges on the existence of a mechanism for turbulent preconditioning of a region much larger than the laminar flame width at that density.

3. Failure of turbulent flame quenching and macroscopic preconditioning

Consider first an infinite fluid dynamical system, containing a passive scalar field that changes from zero to a finite value across the domain of interest, and is subject to self-similar turbulent mixing in the center of the domain. Assuming for now that turbulence or expansion manage to fully extinguish nuclear burning, this is a reasonable description of the temperature field T in the turbulent flame brush, since the length scales we are interested in, $l \sim l_{\rm c}$, are much smaller than the stellar radius and the turbulence on these scales had ample time to establish a self-similar cascade. Under these conditions, the temperature fluctuation amplitudes obey Kolmogorov scaling, $T(l) \sim l^{1/3}$. The temperature field becomes a smooth function at the heat diffusion scale given by $l_{\rm d} \sim L Re^{-3/4} Pr^{-3/4}$ for $Pr < 1$, where Re is the Reynolds number and L is the integral scale of the turbulence. Evidently, increasing the turbulence intensity (and thus Re) decreases the largest length scale where T can be considered smooth, rather than increasing it. Regardless of the amplitude of large-scale turbulent velocity fluctuations, turbulent mixing is inherently unable to provide microscopically mixed regions on macroscopic scales $l_{\rm c}$. Dropping the simplification of treating T as a passive scalar further strengthens this statement, as burning strongly enhances temperature fluctuations on scales $\sim \delta \ll l_{\rm c}$.

The question of DDT in the presence of temperature fluctuations was recently investigated numerically by Montgomery et al. (1998). It was found that perturbation amplitudes of 10-15% are sufficient to divide the gradient region into subregions, each of which would need to have the size of the unperturbed critical length $l_{\rm c}$ in order to give rise to a detonation. However, this study optimistically assumed that a constant temperature gradient of order $l_{\rm c}^{-1}$ exists initially and is subsequently perturbed by turbulent fluctuations on smaller scales. As argued above, these initial conditions are inconsistent with a self-similar turbulent mixing region.

One may also drop the assumption of self-similarity by looking at the special case of a locally isolated fluid element, recognizing that while these are not typical regions of a turbulent flow, a small number of them may be realized on statistical grounds. Consider, for instance, a single large eddy of size $\sim l_{\rm c}$ with little or no entrainment of material from the outside. In this case, the passive scalar is mixed microscopically over the entire region after approximately one eddy turn-over time $\tau_{\rm eddy}(l_{\rm c})$. This situation would, in fact, give rise to suitable preconditioning for DDT if burning could be inhibited during the mixing process; otherwise, small scale fluctuations on the scale δ are continually resupplied. The remaining question is thus: can turbulence quench nuclear reactions in a region as large as $l_{\rm c} \gg \delta$? More specifically, can the burning products contained in $V_{\rm c}$ be cooled sufficiently such that the burning time scale $\tau_{\rm b} \sim \dot{w}^{-1}$, where $\dot{w}$ is the fuel consumption rate, is larger than $\tau_{\rm eddy}(l_{\rm c})$ everywhere within $V_{\rm c}$?

The answer is no, provided that heat loss to the environment is negligible and the flow is subsonic. For simplification, we shall concentrate on carbon burning alone, since it represents the fastest reaction and its extinction is a necessary (and sufficient) condition for flame quenching. Ignoring the small density change across the flame, the carbon burning rate $\dot{w}_{\rm C+C}$ depends only on temperature and carbon mixture fraction. Note further that because of electron degeneracy, heat diffuses many orders of magnitude more rapidly than nuclei, so that we can safely assume that carbon is non-diffusive. Consequently, flame quenching can only occur by diffusive cooling ($p{\rm d}V$-cooling is irrelevant because the flow is to a very good approximation incompressible). Turbulence affects the efficiency of diffusion by straining the flame and thus steepening the temperature gradients. For temperature gradients of order δ^{-1}, the diffusion time scale, $\tau_{\rm d}(\delta) \sim \delta^2/\kappa$, is by definition of δ comparable to the burning time scale $\tau_{\rm b} \sim \dot{w}_{\rm C+C}^{-1}$. For gradients larger than δ^{-1}, diffusion is faster than burning throughout most of the flame. However, it can lead to full extinction only if the entire region of burning products that it is connected with is also smaller than $\sim \delta$, in which case heat can leak out to all sides and the products can be cooled sufficiently to satisfy $\tau_{\rm b} \ll \tau_{\rm d}$. Otherwise, if the flame is connected to a heat bath of burning products larger than δ, the temperature at the interface of fuel and ash always remains fixed at the final product temperature, keeping $\tau_{\rm b}$ small in its immediate vicinity, regardless of the strain rate experienced by the flame. The total burning rate may drop with respect to the flamelet regime, but fast nuclear burning is never fully extinguished within the whole volume.

According to these arguments, the only conceivable way to quench the flame in a large volume $V_{\rm c}$ is to stretch it into a thin filament with thickness $\leq \delta$ and curl it up such that it fills $V_{\rm c}$. In order to prevent unquenched burning in any part of $V_{\rm c}$ before the onset of the spontaneous runaway, this curling has to be completed in a time $t \ll t_{\rm s}(l_{\rm c})$. Interestingly, we now face the same problem as the fractal model described in the previous section: the eddy velocity has to be supersonic in order to prepare the runaway region before it is burned. Again, we are limited by the fact that a subsonic process cannot set up conditions that are later supposed to burn with a supersonic phase velocity.

The line of arguments above is supported by numerical (Poinsot et al. 1991) and experimental (Shy et al. 1996) evidence that premixed chemical flames can only be quenched in the presence of heat losses or complicated thermochemical effects, both of which are absent in thermonuclear combustion. Further confirmation was obtained with a one-dimensional calculation of a thermonuclear flame subject to discrete multiscale remappings representing turbulent eddies (Lisewski et al. 1999). The interaction of simple diffusion-reaction flames with turbulence on the scale of the flame width was studied by Niemeyer et al. (1999), demonstrating that local flame propagation is nearly unaffected by turbulence even if the turbulence intensity is comparable to the laminar flame speed.

4. Alternative scenarios

If the initial deflagration phase fails to release enough energy to unbind the star and no DDT takes place during the expansion, the star pulses and eventually recontracts, revitalizing the turbulence by compression (Arnett & Livne 1994; Khokhlov 1995). During the pulse, the cut-off scale for temperature fluctuations $l_{\rm d}$ can grow extremely large because turbulence is essentially frozen in. At very low densities the flame width δ is macroscopically large, allowing the formation of fluid regions which – if they survive the recontraction phase without disruption – may be suitably preconditioned for DDT later on. However, turbulent entrainment of hot and cold material during the collapse will again raise the amplitude and lower the cut-off scale of temperature fluctuations. It is impossible to say a priori whether the fluid is more likely to reignite in the deflagration or detonation mode. While the extensive mixing period during the pulse probably helps to create favorable conditions for DDT, its benefits may well be erased by the enhanced turbulence intensity during the recontraction. Moreover, the extremely fine-tuned time synchronization required for the gradient mechanism for DDT seems to be as unnatural in the pulsational mode as in the direct one.

An additional problem of the pulsational delayed detonation scenario was pointed out by Niemeyer & Woosley (1997): if a large pulse is needed to achieve the required degree of homogeneity, what are the observational counterparts of those events that barely unbind the star but do not detonate? One may evade this problem by assuming that turbulent deflagrations reliably fall short of releasing the binding energy of the white dwarf. This, however, is in conflict with the latest two-dimensional simulations that indicate a clear trend toward higher energy release with increased numerical resolution (Hillebrandt et al. 1999). These simulations employ a flame capturing algorithm based on the level set method (Reinecke et al. 1998b) that shows the emergence of more and more flame structure as the grid resolution is improved. For certain initial conditions, the star clearly becomes unbound, yet no convergence of total energy generation with respect to resolution has been achieved so far. Should this trend continue, and ultimately be confirmed in three-dimensional calculations, there is a realistic possibility that turbulent deflagrations alone are sufficient to power the explosions without the need for detonations.

The simulations by Niemeyer et al. (1996) and Reinecke et al. (1998a) further demonstrate that the role of the initial conditions for flame ignition has not yet been fully explored. If the explosion is sparked off at many disconnected points, the complexity of the flame surface later on may easily exceed the surface area derived from the non-linear growth of an initially smooth, RT unstable interface ("dandelion model", Niemeyer & Woosley 1997). One-dimensional SN Ia models are unable to adequately represent such effects.

Finally, we can consider alternative routes to detonations that do not rely on large scale preconditioning. One such possibility is active turbulent combustion (ATC) (Kerstein 1996; Niemeyer & Woosley 1997), a runaway process of turbulent combustion that may occur as a consequence of flame-generated turbulence on multiple scales. Scaling arguments show that in the absence of an effective mechanism for stabilization, a runaway must ensue in any unconfined turbulent flame brush (Kerstein 1996). It is possible that the non-linear stabilization mechanism of the Landau-Darrieus (LD) instability by cusp formation (Zeldovich 1966) is unstable with respect to finite amplitude perturbations exerted by turbulent fluctuations, giving rise to an increasingly more violent acceleration of the flame front that ends only when compressibility effects become important. Cusp stabilization of the LD instability may also break down at a critical expansion ratio of burned and unburned material, as suggested by Blinnikov & Sasorov (1996). Practically, the consequences of ATC would involve either nearly sonic turbulent combustion or direct DDT by shock formation ahead of the combustion front. While undoubtedly speculative, ATC is a promising mechanism for powerful SN Ia explosions without the need for fine-tuning. Numerical experiments designed to measure the relevance of ATC for thermonuclear flames are underway.

5. Conclusions

This paper argues that the gradient mechanism for deflagration-detonation-transitions (DDT), previously believed to be the most realistic candidate to explain delayed detonations in Type Ia supernovae (SN Ia), is inconsistent with the phenomenology of turbulent mixing and combustion. Combining the inability of turbulence to provide microscopic mixing over macroscopic length scales with the robustness of thermonuclear flames with respect to quenching, the establishment of sufficiently large regions with a nearly constant temperature gradient is shown to be very unlikely. Both of these effects can (and must) be verified by means of direct numerical simulations on small scales. Work in this direction is in progress; first results of flame-turbulence interactions on small scales can be found in (Niemeyer et al. 1999). The argument above holds as well for pulsational explosions, although here the long intermediate period of diffusion dominated mixing may slightly facilitate the preconditioning needed for DDT.

Why, then, do one-dimensional explosion models with a slow deflagration phase followed by a delayed detonation so successfully fit the majority of SN Ia observations? Either we are missing an important effect that robustly leads to a DDT or at least to a very fast turbulent flame late during the explosion – a noteworthy, albeit speculative, possibility is active turbulent combustion (ATC) – or 1D models get the right answer for the wrong reasons, because they cannot accurately represent important multidimensional effects. An example for the latter is the impact of multipoint ignition on the development of the flame surface complexity, an effect that may well lead to a strongly enhanced burning rate in the deflagration mode as compared with the standard scenario. In any case, the success of both the direct and the pulsational modes for DDT hinges on a deflagration phase that is much slower than indicated by recent results of two-dimensional simulations.

On the other hand, there is a trend toward higher energy release by the turbulent flame if the numerical resolution is increased. So far, no convergence of the total energy generation has been attained. If this trend continues and is confirmed by three-dimensional calculations with realistic subgrid-scale modeling, the possibility that the bulk of Type Ia supernovae explodes without ever detonating must be taken more seriously.

To summarize, our analysis suggests that detonations may never take place in SN Ia explosions. If they do, they probably need to be preceded by a nearly sonic turbulent deflagration, in which case it may not be possible to clearly distinguish deflagrations from detonations observationally. ATC, multipoint ignition, higher than anticipated energy release in the turbulent flame brush, or any combination thereof may provide the required energy output to power the explosion.

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REFERENCES

Arnett, D. and Livne E. 1994, ApJ, 427, 330

Blinnikov, S. I. and Sasorov, P. V. 1996, Phys. Rev. E, 53, 1

Hillebrandt, W., Reinecke, M., and Niemeyer, J. C. 1999, Comp. Phys. Comm., in press

Höflich, P., Khokhlov, A. M., Wheeler, J. C,. Phillips, M. M., Suntzeff, N. B., and Hamuy M. 1996, ApJ, 472, L81

Kerstein, A. R. 1996, Comb. Sci. Tech., 118, 189

Khokhlov, A. M. 1991, A&A, 246, 383

Khokhlov, A. M. 1995, ApJ, 449, 695

Khokhlov, A. M., Oran E. S., and Wheeler, J. C. 1997a, Combust. Flame, 108, 503

Khokhlov, A. M., Oran E. S., and Wheeler, J. C. 1997b, ApJ, 478, 678

Lee, J. H. S., Knystautas, R., and Yoshikawa, N. 1978, Acta Astronaut., 5, 971

Lisewski, A. M., Hillebrandt, W., Woosley, S. E., Niemeyer, J. C., and Kerstein, A. R. 1999, in preparation

Montgomery, C. J., Khokhlov, A. M., and Oran, E. S. 1998, Combust. Flame, 115, 38

Niemeyer, J. C. and Hillebrandt, W. 1995, ApJ, 452, 769

Niemeyer, J. C., Hillebrandt, W., and Woosley, S. E. 1996, ApJ, 471, 903

Niemeyer, J. C. and Kerstein, A. R. 1997, New Astronomy, 2, 239

Niemeyer, J. C. and Woosley, S. E. 1997, ApJ, 475, 740

Niemeyer, J. C., Bushe, W. K., and Ruetsch, G. R. 1999, ApJ, in press

Nomoto, K., Iwamoto, K., and Kishimoto, N. 1997, Science, 276, 1378

Peters, N. 1984, Prog. Energy Combust. Sci., 10, 319

Poinsot, T., Veynante, D., and Candel, S. 1991, J. Fluid Mech., 228, 561

Reinecke, M., Hillebrandt, W., and Niemeyer, J. C. 1998a, A&A, in press

Reinecke, M., Hillebrandt, W., Niemeyer, J. C., Klein, R., and Gröbl, A. 1998b, A&A, in press

Shy, S. S., Jang, R. H., and Ronney, P. D. 1996, Combust. Sci. Tech., 113, 329

Woosley, S. E. 1990, in Supernovae, ed. A. Petschek, (D. Reidel: Dordrecht), 182

Woosley, S. E. and Weaver, T. A. 1994, in Les Houches, Session LIV, Supernovae, ed. S. Bludman, R. Mochkovitch, and J. Zinn-Justin (Amsterdam: North-Holland), 63

Zeldovich, Ya. B. 1966, J. Appl. Mech. Tech. Phys., 7, 68

Zeldovich, Ya. B., Librovich, V. B., Makhviladze, G. M., and Sivashinsky, G. L. 1970, Astronaut. Acta, 15, 313